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Experimental and numerical study for detection of rail defect

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ABSTRACT

Condition monitoring methodologies have become an important part in maintenance programs for any type of structure towards prevention of catastrophic accidents. Natural frequency analysis is a useful methodology to evaluate the integrity condition of structural elements, such as: rotor beams, rails and almost every machine component. In this work, two techniques were applied for condition monitoring of rails: numerical, using the Finite Element Method (FEM), and experimental analysis. Sections of a rail 115RE had been characterized in the field for integral track section and laboratory for integral and artificial cracks conditions at different depths, in free-free boundary condition. Numerical simulation was used to compare and validate the experimental analysis. The changes in natural frequencies were observed as a function of the crack depth. It was performed a sensitivity analysis of natural frequency variation due to the influence of the crack depth and the section dimensions in order to explore the behaviour in modes of vibration. In addition, this monitoring technique can be potentially used as a criterion of when is necessary whether or not to eliminate the crack by gridding or replace the entire rail section. Finally, the finite element simulation was validated throughout natural frequencies measurements in the railway network.

1. Introduction

The use of railways systems has increased in recently years; either in passenger and heavy haul transportation. Railway systems must have high reliability and system security which requires the minimization of the malfunctions caused by inadequate and inopportune maintenance, therefore, saving money, energy and increase lifespan system.

Railways vehicle consists of many sub-systems; however, in particular the wheels are in close interaction with the railway track [1]. Normally, the contact area between the wheel and rail is an ellipsoidal shape with 1 cm^2 area. Wheel-rail interaction is a condition which appears on rails as a result of repeated overstressing on the surface or subsurface by after millions of cycles generating Rolling Contact Fatigue (RCF), wear, crack propagation and global vehicle performance reduction [2,3].

Non-destructive testing (NDT) is the use of physical methods to test materials; components and assemblies systems for looking at detect faults in any structure without damaging their future usefulness and functions. NDT is concerned to reveal flaws in the structure. However, it cannot predict where potentially the faults will develop. So, the development of monitoring methodologies allow to have a possible prediction of the behaviour of structural systems.

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On the other hand, researchers have developed condition monitoring techniques in rails using cameras, sensors, computer processers, etc. looking at the necessities of the railway industry. One of the known techniques for monitoring is based on track stiffness measurement; this technique is a rather common method to monitor rail condition [4–6]; while acoustic emission technique is another method based on propagation of sound waves for continuous and detecting faults in rails [7]. Finally there are another techniques based on the response of the track induced by external excitation [8].

Oregui et al. developed an experimental investigation in order to determine the structural condition of the Insulated Rail Joints (IRJ) using the dynamic response from an impact excitation for different damaged states in the rails [9]. The technique shows the potential to monitor and assess the condition of IRJ through an analysis of dynamic responses due to hammer impact excitation or wheels passing over the gap of IJR. In addition, Oregui et al., used a Finite Element (FE) modelling to simulate a hammer test with the purpose of identified the dynamic parameters of the track which could help to developed adapted maintenance methods or track design to prevent or avoid defects [10].

Kaewunruen and Remennikov integrated field measurements and track simulation in order to develop a NDT approach for the dynamic condition in railway track structures [11]. The research presents an alternative NDT technique to evaluate the integrity of track structure for two defects: damaged rail fastener (e-Clip) and a cracked sleeper. Esveld and Amy De Man proposed the use of vibration behaviour of the railway track structure in the mid- and high-frequency range that can act as an indicator for the performance of the track structure with respect to the sound radiation, vibration sensitivity and wheel-rail interaction forces [12].

In the present study, numerical and experimental analyses of a rail 115RE were developed. The first natural frequencies were calculated for integral and damaged rail sections with artificial cracks with different levels of damage (cracks depth), also the rail length behaviour with a crack was simulated, and finally, the variation of the crack at different positions along the rail in FE analysis was simulated. Crack initiation and the very early crack propagation stage are not studied in the present article. In the experimental analysis, the first five natural frequencies were obtained for integral and damaged condition with a crack at the half of the length of rail. Finally, this work presents an alternative NDT technique and criteria to evaluate the integrity of track structures.

2. FEM rail model

A rail section (115RE) was modelled by CAD software (FE) and simulated in ANSYS software with a standard length of 0.6 m between sleepers. The elements used for the analysis were: Solid185 for the 3-D solid structure and 8-Node surface-to-surface Contact-174 and 3D Target-170 for the rail-sleeper interaction (Fig. 1(a)). In order to obtain the natural frequencies, two different boundary conditions were simulated: Free-Free (FFC) and real supported (RSC). A convergence analysis was performed to optimize the mesh (Fig. 1(b)). The mechanical properties used for the analysis are shown in Table 1, while the geometrical properties of the rail were obtained from a technical manual [13]. The FE analysis was carried out comparing the experimental test frequency analysis (Fig. 2).

3. Natural frequency analysis

Natural frequency analysis (NFA) is the process of determining the inherent dynamic parameters of the system [14]. The knowledge of the modal parameters can offer various purposes including: structural modification, evaluation of the structural integrity and reliability, condition monitoring and model updating [15–18]. NFA embraces both theoretical and experimental techniques. In this study, the natural frequency parameter was selected to perform a vibration based damage detection analysis and also to validate the FE model.

The idealized elements of the physical system can be described by the equation of motion (Eq. (1)).

$$m\ddot{x} + c\dot{x} + kx = f(t) \tag{1}$$

Solving Eq. (1), when harmonic forcing is applied, it was able to describe the complete solution by a single matrix called "Frequency response matrix" [H (ω)] and it consisted in solving an eigenvalue problem where every natural frequency corresponds a

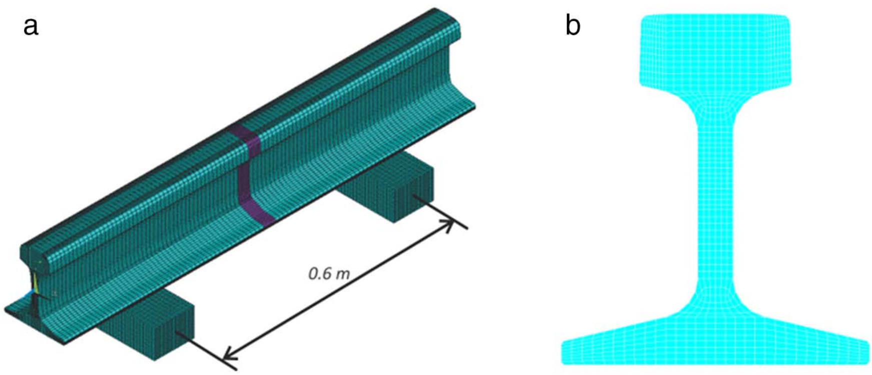

Fig. 1. Finite element model of rail 115RE: (a) integral rail condition and (b) rail mesh cross section.

Table 1
Mechanical properties of track components.

Rail length (m)	0.6	Rail Young's Modulus (GPa)	210
Rail density (kg/m3)	7750	Sleeper Poisson's ratio	0.18
Rail Poisson's ratio	0.3	Sleeper Young's Modulus (GPa)	47.5

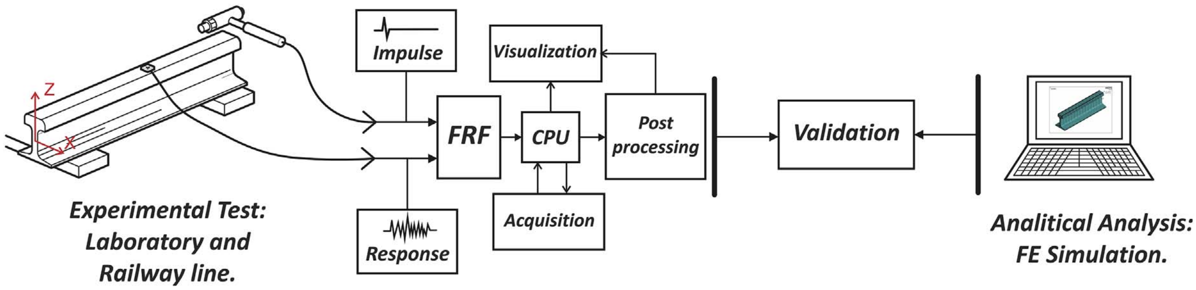

Fig. 2. FE model validation through experimental and laboratory test.

modal shape. Eq. (2) is the foundation of the testing in this work.

$$H_{jk}(\omega) = \frac{X_j}{F_k} \quad (2)$$

X_j represents the harmonic response in one of the degrees of freedom, j, caused by a single harmonic force F_k applied at a different degree of freedom, k.

4. Validation of finite element model

Natural frequency behaviour was investigated using FE simulation and validated by experimental test from laboratory (Fig. 3(a)) and railway network in Mexico City (Fig. 3(b)), considering an integral rail section to perform NFA (Fig. 2).

The natural frequencies of the integral rail were measured in free-free condition in laboratory and also in RSC to simulate the railway line conditions. The experimental equipment was integrated by: National Instruments data acquisition module, PCB impact hammer, triaxial accelerometer PCB and LabView software. The experimental tests were realized with the application of an excitation force in four points along the spam of the rail with three hits at each excitation point (EP) in the vertical direction; see Fig. 3(a). The signals were measurement in two directions X and Z as show in Fig. 4. The acquired data were processed in order to obtain the Frequency Response Function (FRF) graph.

Several soft support conditions were tested in order to be close to the ideal free-free condition, from hanging the rail in elastic chords to posing it on inflated tire rubber chambers. This last method showed the better results compared to numerical results.

The correlation between the results obtains from Finite Element model for an integral rail section in laboratory and field test were satisfactory. Fig. 4 shows the natural frequencies in X and Z directions of measure from experimental and numerical analysis. The differences in analytical and experimental results were attributed to: the general problems inherent in the measurement technique, the FE model is generated with certain idealization and assumptions that describe the system as close as possible to physical conditions, etc.

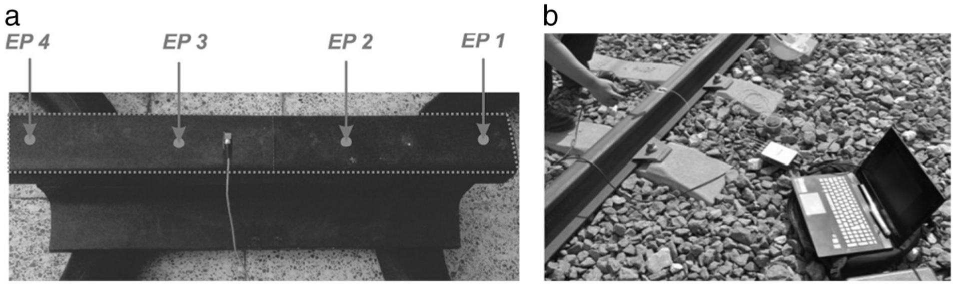

Fig. 3. Experimental set up of rail 115RE: (a) In laboratory and (b) Railway network of Mexico City.

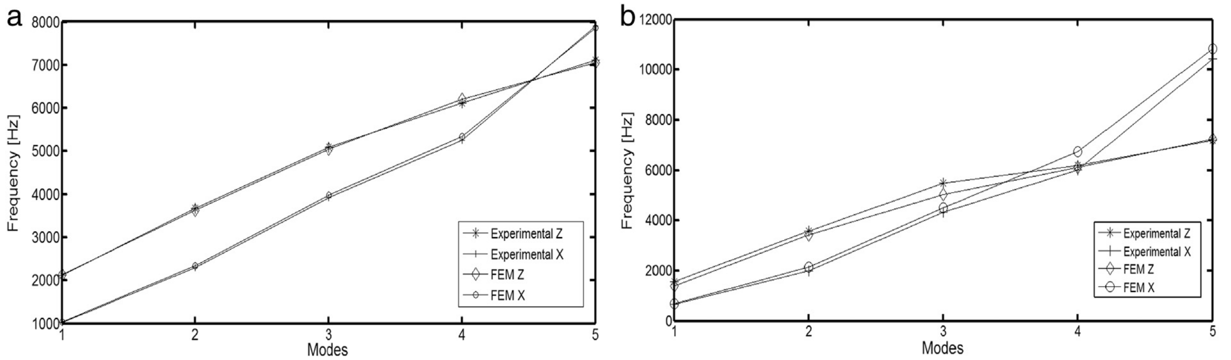

Fig. 4. Comparison between Experimental and FEM results for integral rail 115RE (a) FFC and (b) RSC.

5. Crack model

The cracks in rails may initiate near surface area or at the surface and propagates below the surface due to high traction forces between the rail and wheel contact, this phenomena is called Rolling Contact Fatigue (RCF). Several studies of crack growth rates in wheel-rail interaction are published in the literature [19–21]. The critical size of a crack should be defined as the size that can be expected to cause failure in the structure, this crack size can be estimated according to Linear Elastic Fracture Mechanics (LEFM) from the stress intensity factors compared to the material toughness. If needed, the growth rate of cracks could be determined using some models such as the well-known Paris law equation, among others like Erdogan, Forman, Walker, Ratwani, Klesnil and Lukas [22]. However, this aspect is not covered here, since the dynamic behaviour of the damaged rail is the main issue in the present study [22].

The effect of crack damage was simulated and tested, varying the crack position and the length of the rail with four levels of crack depth. The results were obtained for two cases:

- *First case*: In laboratory, the experimental model was developed producing an artificial open crack with a "gap" across the rail head in FFC, a 0.6 mm crack thickness was made at the top of the rail at the middle of the rail by a saw machine, four different levels of crack depth were reproduced: Depth1 = 0.5 mm, Depth2 = 1 mm, Depth3 = 1.5 mm and Depth4 = 2 mm. The experimental set up was validated with FE simulation (Fig. 5(a)).

- *Second case*: FE analysis was performed to determinate the behaviour of the rail length when a crack is present. Simulation for the FFC as well as railway track boundary conditions (RSC), were accomplished. The defect is modelled as an internal crack caused by RCF located at the head of the rail as shown in Fig. 5(b). It was investigated the changes in natural frequencies according to the crack size, four lengths of the crack were simulated: 1 mm, 2 mm, 4 mm and 6 mm. Also, three different crack positions along the length of the rail at 1/2, 1/4 and 1/3 were considered [23,24].

6. Results

6.1. First case

Experimental analysis (EA) was performed for the first five flexural frequencies in two directions as mention above for integral and damaged rail sections with different crack depths. Fig. 6 shows the FRF's of the integral rail.

Meanwhile, in Fig. 7(a)–(e) a comparison between the integral and the damaged rail condition with four different levels of crack

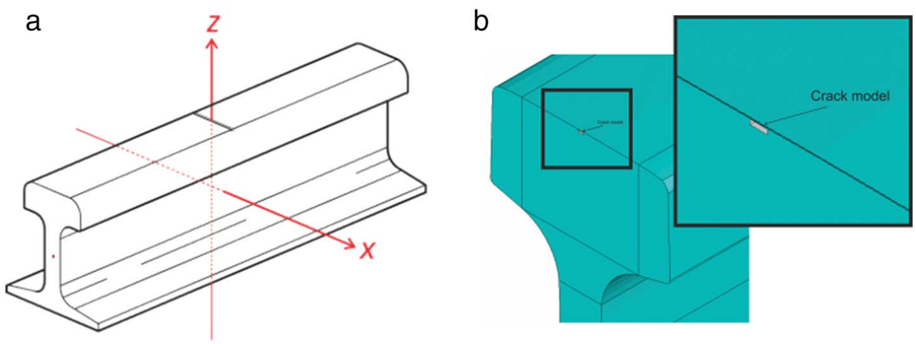

Fig. 5. Visualization of the115RE model: (a) Laboratory crack and (b) FE crack simulation.

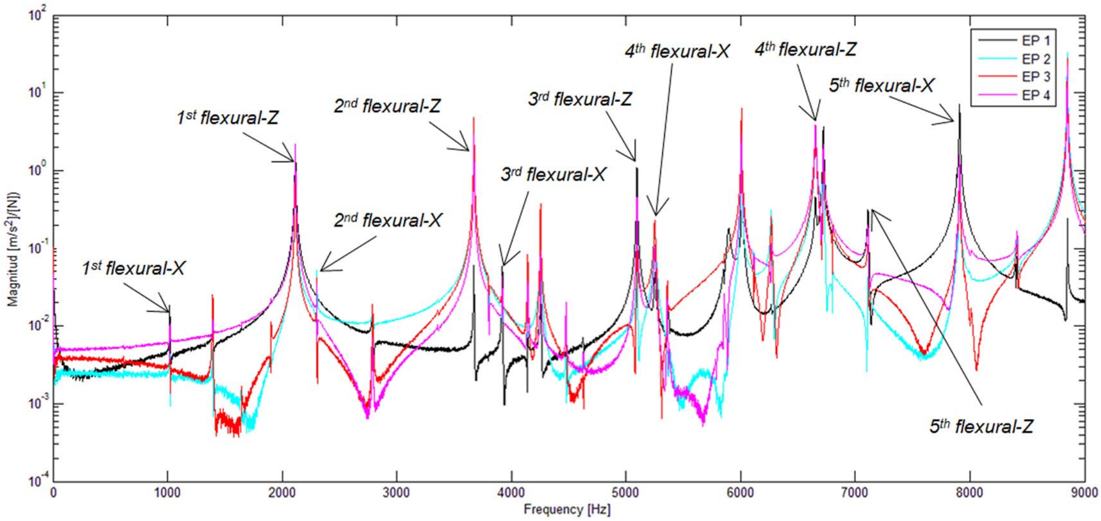

Fig. 6. Experimental FFR graph for integral condition of rail 115RE with four excitation points in FFC.

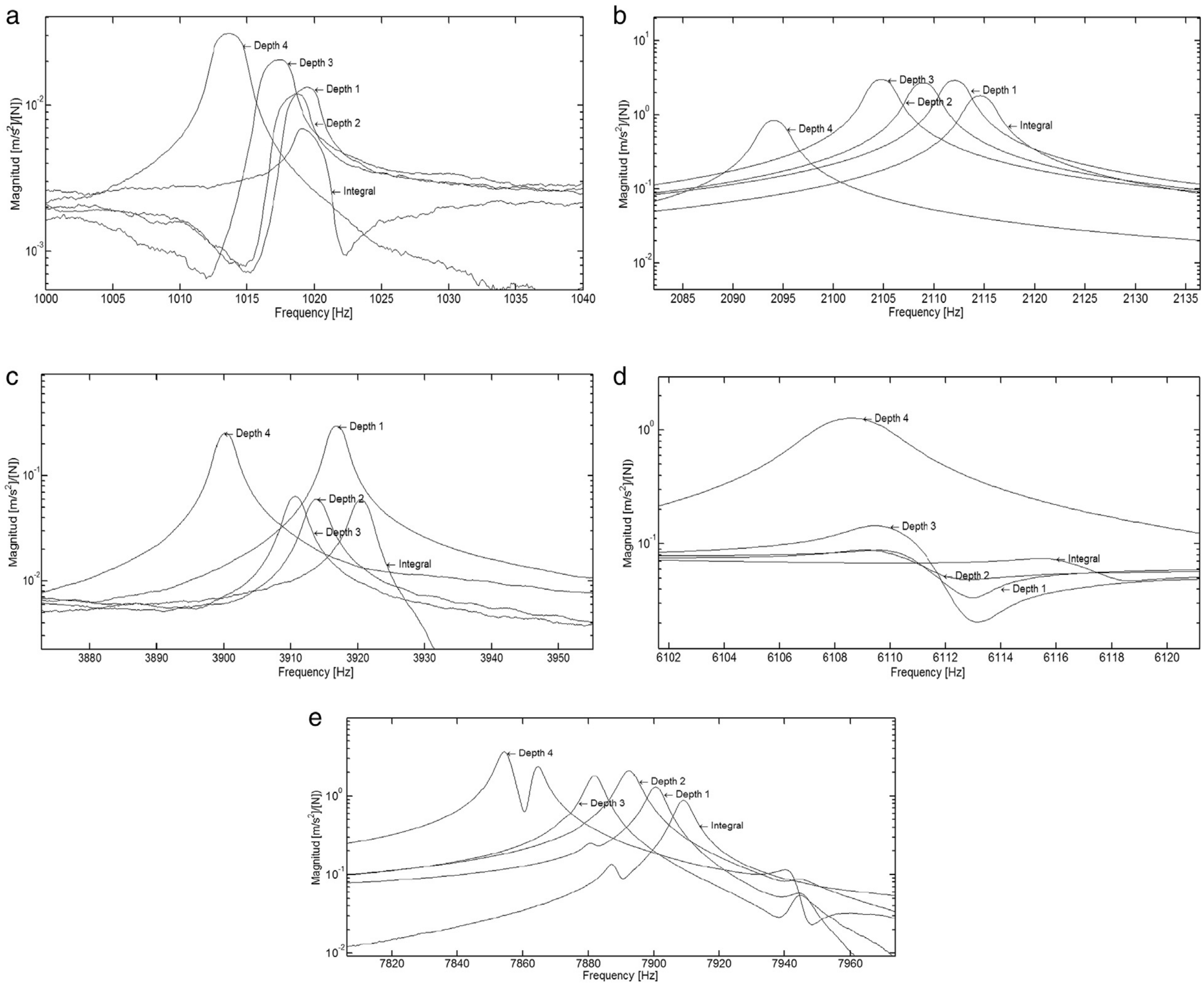

Fig. 7. Variation in natural frequencies due to depth cracks for FFC rail at modes: (a) 1st flexural *X* direction, (b) 2nd flexural in *Z* direction, (c) 3rd flexural in *X* direction, (d) 4th flexural in *Z* direction and (e) 5th flexural in *X* direction.

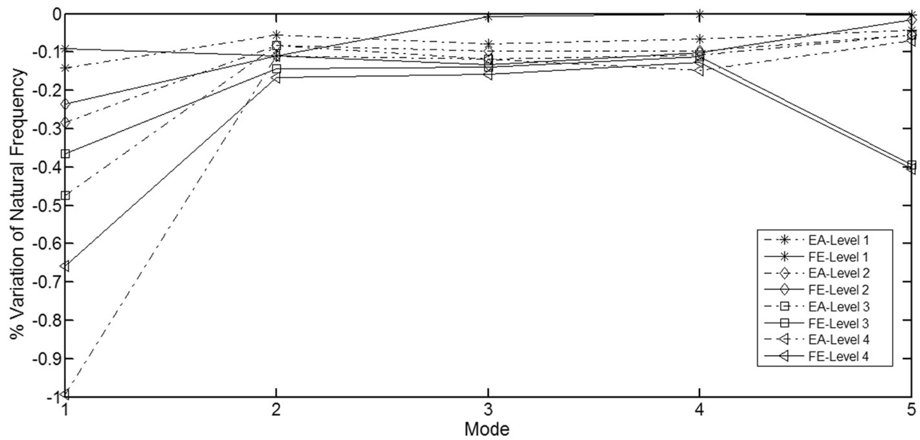

Fig. 8. Percentage variation of natural frequency between EA and FE results for damage conditions in Z direction.

depth can be observed.

Figs. 8 and 9 show the percentage variation of natural frequencies between Experimental Analysis and numerical FE results for the first five modes of vibration with the four levels of crack depth for each direction in FFC. The percentage variation of natural frequencies was calculated using Eq. (3); $nf_{\mathrm{Nintegral}}$ is the natural frequency for integral rail section and nf_{Ndamaged} is the natural frequency for the crack rail section for the N mode. Also, in the Figures can be observe the variation of the natural frequency due to the crack depth.

$$\%\mathrm{Variation}_{\mathrm{N}} = \frac{nf_{\mathrm{Ndamaged}} - nf_{\mathrm{Nintegral}}}{nf_{\mathrm{Nintegral}}} \times 100 \tag{3}$$

6.2. Second case

In Fig. 10 shows the FE results of the damaged model with four crack depths located at the half length of the rail. The rail was simulated under RSC.

On the other hand, the deepest crack was modelled (Level 4) at three different axial locations: 1/3, 1/4 and 1/2 of the rail length. Figs. 11 and 12 show the variation of natural frequencies due to the crack position for the first five modes in Z and X directions for FFC and RSC respectively in FE simulations.

In Fig. 13 shows the first five modes shapes of an integral beam with the superimposed cracks positions. The graph is useful to understand why the crack location affects some more modes than others. For instance, when the crack position is at the half length (Crack 1/2), the modes 2 and 4 are unaffected, since the position is a node for those modes. On the other, for crack position at 1/3, the mode 3 is unaffected, and mode 4 is affected, finally crack position at 1/4 the modes 4 and 5 are affected.

Moreover, in the FE analysis, it was considered whether or not the variation of the length has a particular influence on the frequency tendency. Therefore, three different lengths of the rail were simulated: 0.3 m, 0.6 m and 1.2 m with the deepest crack at the half length of the rail in RSC, see Fig. 14.

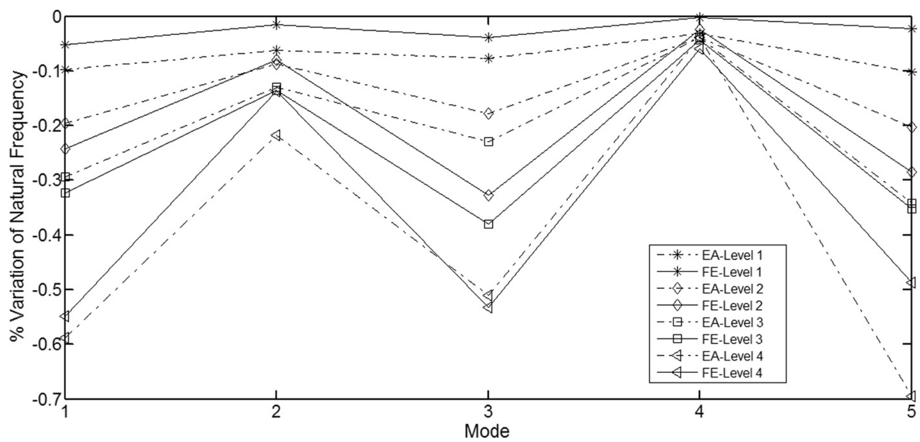

Fig. 9. Percentage variation of natural frequency between EA and FE results for damage condition in X direction.

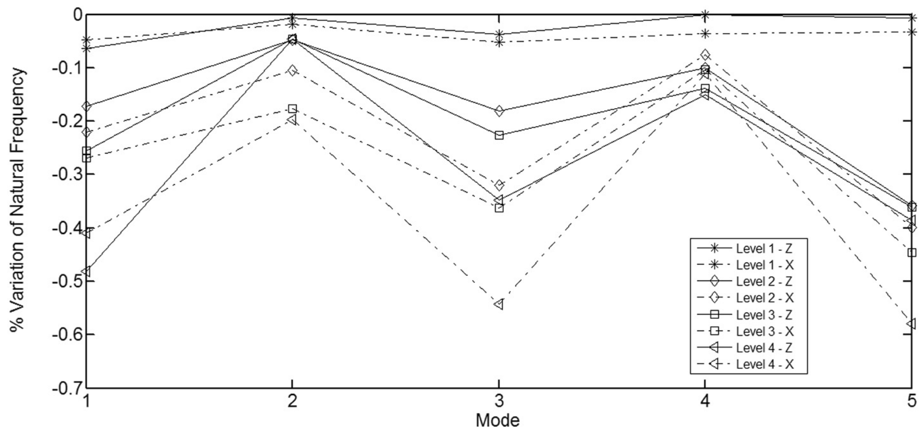

Fig. 10. Percentage variation of natural frequency for FE results with crack at the middle between integral-damage condition for RSC in *X* and *Z* directions.

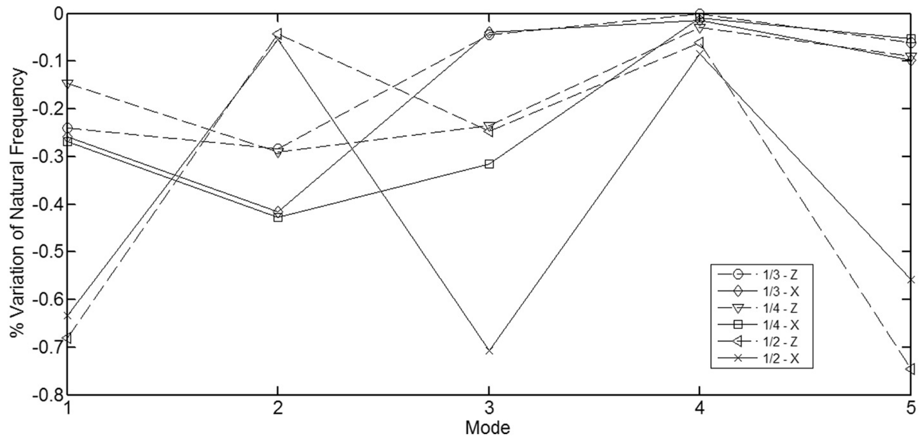

Fig. 11. FE results: natural frequency variation of the rail for FFC in *Z* and *X* directions for level deepest crack.

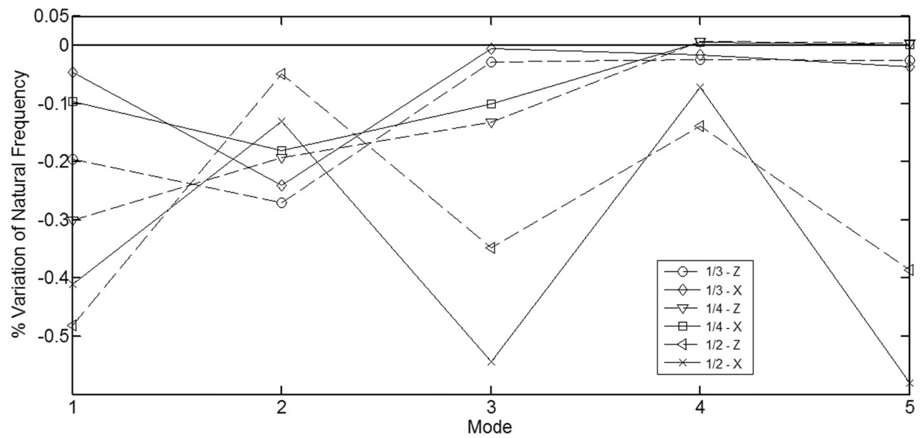

Fig. 12. FE results: natural frequency variation of the rail for RSC in Z and *X* directions for level deepest crack.

7. Discussion

Despite of difficulties to access a real railway line, this work represents a good validation of the FE model compared to experimental tests (laboratory and field) for integral railway track. The obtained results were satisfactory, as shown in Fig. 4. The main objective was to develop a confident FE model to characterize a damaged condition and find the natural frequencies tendency to help develop maintenance methodologies.

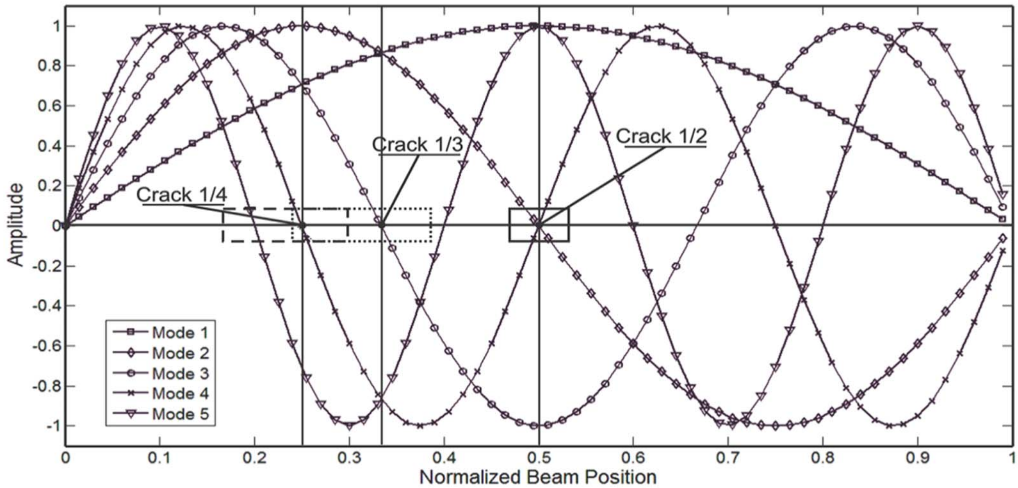

Fig. 13. Crack position and modes shapes for rail section condition (simply supported).

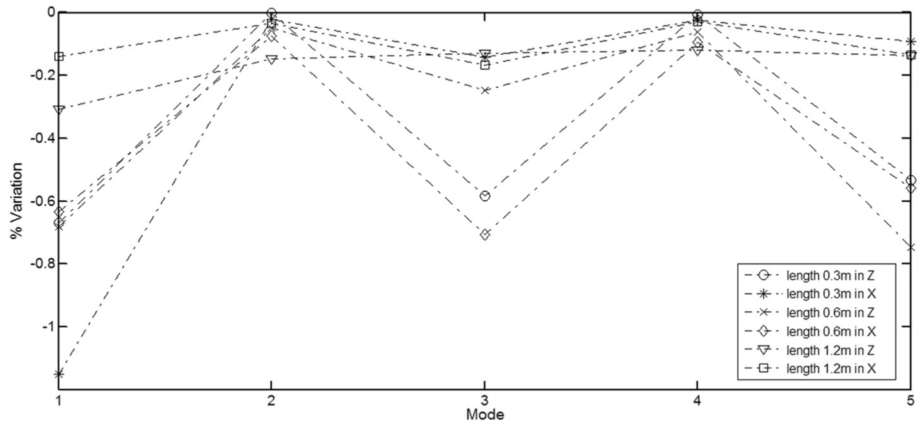

Fig. 14. Percentage variation of natural frequencies for different rail lengths (with deepest crack, Level 4) in *Z* and *X* directions.

The natural frequencies change with crack depth and location; for instance, the first flexural mode is mainly reduced in Z direction; however, the largest difference for each crack depth was obtained in the experimental method, therefor, FE results the first and the fifth flexural modes also decreased significantly. On the contrary, in X direction, the first, the third and the fifth natural frequencies decreased in both experimental and FE analysis (see Figs. 8, 9 and 10).

In both directions of measurement, for the second and fourth frequencies, not a significant change was observed (Figs. 8, 9 and 10). This behaviour is because of influence of crack position in the modal shape, since the nodal point is coincident or close to the same location of the crack (Figs. 11 to 13).

Overall, the changes in the structural stiffness by rolling/sliding damage normally lead to a variation of natural frequencies. The variations of natural frequencies can be represented in a percentage which can also be used as a criterion towards identify and relate the possible presence and position of cracks in a maintenance program. Additional research (simulations and experimental work) should be carried out in order to achieve even more accurate prediction of the presence and position of the cracks.

Take into account the variations in natural frequencies, it is possible to detect faults (cracks), but if it decides to take maximum advantage of the technique, it is recommended to have a large Condition Based Maintenance (CBM).

Finally, In Fig. 14 is corroborated that no matter what length the rail has, it had not a change in frequency trend, but the magnitude of the frequency value decreases when the rail length increases.

8. Conclusion

According to results, the NFA methodology has been proved to be efficient to detect cracks and possible position in rail structures. The structural stiffness is an indicator weather or not the system presents a significant defect, so them the technique could detect damaged by performed natural frequency analysis.

The FE model was validated thought out experimental test results reproducing different depths and crack positions.

The propose technique has several advantages compare to NTD techniques: such as: detect more than one defect in the rail and could be incorporated in full track maintenance programs.

If the technique is applied as a continuous monitoring, a medium to large data based could be necessary.

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